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# Off-Hugoniot characterization of alternative inertial confinement fusion ablator materials.

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**Abstract.** The ablation material used during the National Ignition Campaign, a glow-discharge polymer (GDP), does not couple as efficiently as simulations indicated to the multiple-shock inducing radiation drive environment created by laser power profile [1]. We investigate the performance of two other ablators, boron carbide (B<sub>4</sub>C) and high-density carbon (HDC) and compare with GDP under the same hohlraum conditions. Ablation performance is determined through measurement of the shock speed produced in planar samples of the ablator subjected to the identical multiple-shock inducing radiation drive environments that are similar to a generic three-shock ignition drive. Simulations are in better agreement with the off-Hugoniot performance of B<sub>4</sub>C than either HDC or GDP.

## 1. Introduction

The ablation of the outer capsule surface by x-rays created in a hohlraum cavity is a key element to the indirect-drive scheme being pursued on the NIF. X-rays generated by the interaction of a purposefully shaped laser pulse incident inside a high-Z, Au or depleted uranium hohlraum result in the ablation of material from the capsule. The rocket-like blow-off of material generates multiple shocks that accelerate the capsule to velocities of  $> 350$  km/s and implode it from an initial diameter of  $\approx 1.0$  mm to  $< 35$   $\mu$ m. The efficiency with which this rocket effect occurs is a result of the x-ray ablation properties of the capsule material, and so is a key-parameter in the quest for ignition. An approximate analytic expression for the ablation pressure can be found by considering the conservation of momentum and energy, and constant specific heat [2]:

$$P_{abl} = (1 - \alpha)(\gamma - 1)\sigma T^4 \sqrt{\frac{Am_p}{(Z + 1)k_B T}} \quad (1)$$

where  $\sigma$  is the Stefan-Boltzmann constant,  $A$  is the atomic number and  $m_p$  is the proton mass. Assuming an albedo ( $\alpha$ ) of approx 0.3 since the ablator thickness is typically tuned to optimize for the material opacity and  $\gamma = 5/3$ , we calculate the average ionization ( $Z$ ) using FlyCHK for a temperature of 110 and 170eV corresponding to typical 1st and 2nd shock conditions [4]. Table 1 shows typical ablation pressures for the different materials, motivating the interest in HDC, B<sub>4</sub>C and Be, where 15-20% enhancement in  $P_{abl}$  might be expected over GDP.

**Table 1.** Estimated ablation pressures for GDP, B<sub>4</sub>C, HDC and Be

	$\rho$ (g/cm <sup>3</sup> )	$A$	$T=110\text{eV}$		$T=170\text{eV}$	
			$Z$	$P_{abl}$ (Mbar)	$Z$	$P_{abl}$ (Mbar)
GDP	1.1	13	7	8.2	8	35.8
HDC	3.5	12	5	9.7	6	41.1
B <sub>4</sub> C	2.4	55	21	10.0	26	41.9
Be	1.9	9	4	9.2	4	42.2

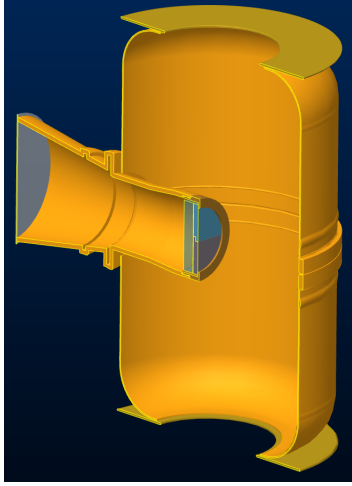
To-date experiments have concentrated on GDP which has the motivating advantage of a long history of development and production of high-quality capsules, together with the ease with which a high- $z$  dopant can be added to reduce fuel pre-heat. Using Be, B<sub>4</sub>C as an ablator actually offers greater margin to reach ignition conditions since they all absorb more energy than CH, having a lower albedo, and therefore offer a higher ablation rate for a given temperature. In addition, since B<sub>4</sub>C and HDC are higher density, they enable a thinner ablator shell to be used while maintaining the same shell mass. This has a two-fold advantage: (1) shorter laser pulses can be used reducing filling of the hohlraum and allowing the use of near-vacuum hohlraums that suffer less backscatter, and (2) for an equivalent outer diameter, the thinner shell can contain more fuel. In addition, higher mass ablation rates provide better ablative stabilization of mix seeded by the outer surface roughness.

The ablation rates of GDP under single-shock ignition relevant conditions have previously been compared to a range of materials including Be and diamond-like HDC at temperatures between 160-260 eV and indicate that better ablation performance can be achieved with Be and HDC to that of GDP [3]. However the standard ignition laser pulse design uses three or four shocks to accelerate the capsule, so by the time that the final shock is launched to set the final implosion velocity ( $v_{imp}$ ), the ablator has experienced two or three previous shocks, so it is the ablation performance under these off-Hugoniot conditions that is of real importance in determining  $v_{imp}$ . To investigate this we compare the relative performance of B<sub>4</sub>C and HDC to GDP under multiple-shock, ignition-relevant conditions and for simplicity of manufacture we make measurements in a planar geometry.

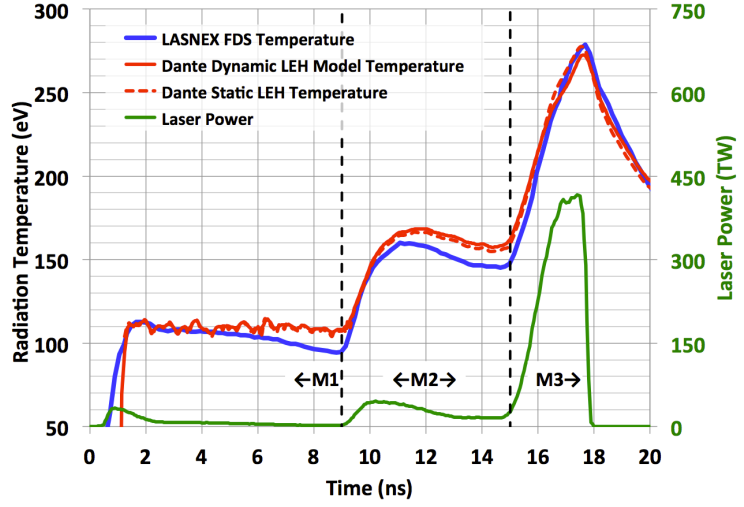
## 2. Methods

We measure the absolute shock velocity obtained for a given ablator material using the NIF VISAR diagnostic [6] and characterize the x-ray energy incident on the ablator by measuring the hohlraum temperature through the laser entrance hole (LEH). The x-ray emission is measured by the NIF Dante diagnostic [7]. The same 5.75 mm diameter by 9.43 mm long hohlraum and laser-beam pointing as in other fusion experiments [5] is used, Figure 1, but we replace the fusion capsule with a 2.0 mm planar disc of the ablator material. The hohlraum is filled to 400 torr with He<sub>4</sub> gas and cooled to 21 K to create a gas-fill density of 1.45 mg/cc. The ablator disc is situated 0.4 mm from the hohlraum axis to create a similar viewfactor of the gold hohlraum wall as a normal ignition capsule. The laser pulse shape is fixed regardless of ablator material to, as-much-as-possible, create a ‘universal’ x-ray drive. The ablator densities were measured by simple weight and volume characterization to within  $\pm 0.01$  g/cc; the B<sub>4</sub>C was 2.51 g/cc, HDC was 3.50 g/cc, and GDP was 1.08 g/cc. The Rq surface roughness was typically 500-800 nm rms for the B<sub>4</sub>C samples 40-60 nm rms for HDC and 140-180 nm for the GDP, all of which are below the minimum cell-size used in calculations - typically  $< 0.5 \mu\text{m}$ .

The shock pressure history of the ablator is measured by adding either a 10  $\mu\text{m}$  gold pre-heat shield and 400  $\mu\text{m}$  of  $\alpha$ -quartz followed by liquid deuterium (D<sub>2</sub>), or only liquid D<sub>2</sub>. The  $\alpha$ -quartz acts as a reference material so that the shock velocity can be used to infer the ablation



**Figure 1.** A planar ablator package replaces the capsule inside an ignition scale hohlraum.



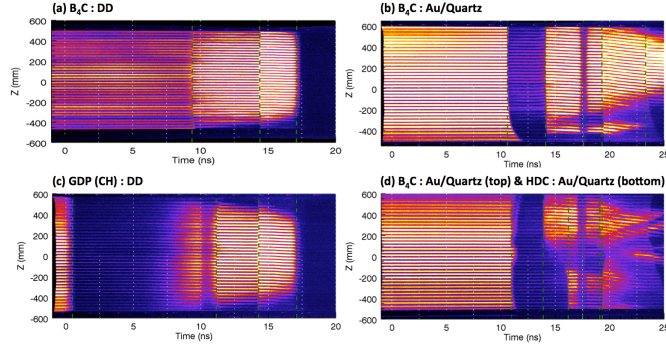
**Figure 2.** Hohlraum radiation temperature measured by Dante: (red - - -) assumes no LEH motion, (red —) dynamic LEH model, (blue) temperature source used in LASNEX simulations, and (green) laser pulse.

pressure from the well-understood equation of state of  $\alpha$ -quartz [8]. Unfortunately experiments using the  $\alpha$ -quartz also necessitate the Au preheat shield. This introduces a shock-impedance mis-match and reflected shock that disrupts the ablation front meaning that the results are less relevant to a fusion capsule. To mitigate this we also perform experiments in which the ablator is backed by liquid deuterium, which is a good surrogate for a DT ice-layer. The equation of state of deuterium under these conditions is less well understood, and also more easily ionized by hot-electrons or few-keV photons generated in the hohlraum, but the shock and release behavior is directly applicable to a fusion capsule performance.

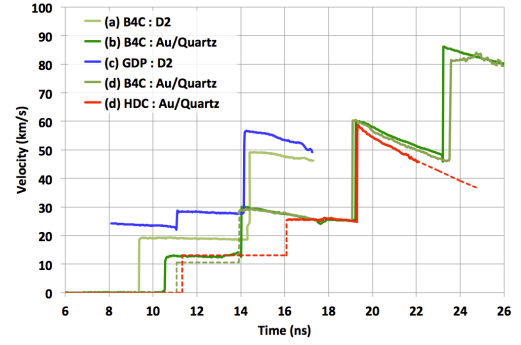
### 3. Results and Discussion

Soft x-ray images of the hohlraum laser-entrance hole (LEH) were used to correct the x-ray flux measured by the Dante instrument in Figure 2 and calculate the radiation temperature for comparison with simulation. Simulations were performed using the ‘High-flux’ model in the radiation hydrodynamics code LASNEX [9]. Once post-processed to simulate the Dante measurement these match the measured temperature very well and within the 5% x-ray flux uncertainty of Dante at the peak. The simulations are tuned to match the shock velocity and overtake times measured by the VISAR diagnostic by applying multipliers (M1, M2 and M3) to the laser power in the three regions shown:  $t < 9$  ns,  $9$  ns  $< t < 15$  ns, and  $t > 15$  ns.

The VISAR data in figure 3 shows nuanced differences in the shock and ablator material reflectivity for the different ablators. In addition to the shock signatures, in figure 3(a) and (c) when the peak laser power is reached at 17.5 ns, the data disappears. This is also coincident with the peak in the hot electron signal inferred from hard x-rays measured by FFLEX and also the greatest production of Au M-band radiation inside the hohlraum. It is postulated that these factors cause the either the D<sub>2</sub> and/or quartz window at the rear of the VISAR cone to be weakly ionized and non transmissive to the VISAR laser. In figure 3(b),(d) and (e) the behavior is different. A reduction in fringe visibility is observed at the same time as in (a) and (c) which is again hypothesized to be the result of hot electrons or hard x-rays from the hohlraum causing the quartz to ‘blank’. However, in these experiments the Au preheat shield limits the duration



**Figure 3.** VISAR data for four experiments (a) N130218: 152.9  $\mu\text{m}$  B<sub>4</sub>C and liquid D<sub>2</sub>, (b) N130114: 149.4  $\mu\text{m}$  B<sub>4</sub>C, 9  $\mu\text{m}$  Au and 402  $\mu\text{m}$   $\alpha$ -quartz, (c) N140719: 250.0  $\mu\text{m}$  GDP and liquid D<sub>2</sub>, and (d) N130524: top: 148.3  $\mu\text{m}$  B<sub>4</sub>C and bottom: 148.6  $\mu\text{m}$  HDC, 11  $\mu\text{m}$  Au and 402  $\mu\text{m}$   $\alpha$ -quartz.



**Figure 4.** Shock velocities: Dotted and dashed lines are calculated based on the shock break-out time from the quartz and assume the shock had constant velocity during the periods missing data; the uncertainty is 0.8  $\mu\text{m}/\text{ns}$

of this effect to about 1 ns, after which the quartz recovers. It is also of note that the data in (b) and the top of (d) are essentially repeated, and so the 0.4 ns later arrival of S1 in (d) is a result of the 2% lower laser energy prior to 9 ns and the 2  $\mu\text{m}$  thicker Au layer.

Obviously M3 cannot be accurately infer from the data in figure 3(a) and (c) due lack of data after the laser power peaks, however, M1 and M2 in figure 3(a) and (c) are directly relatable to an ignition capsule and indicate better agreement between the simulated and measured ablation performance of B<sub>4</sub>C than that of GDP. For all experiments the value of M1 inferred from the tuned simulations was about 1.00, however an M2 multiplier of 1.06, 1.00 and 0.95 was required to match the B<sub>4</sub>C experiments (a), (b) and (d), while M2=0.85 was required to match the HDC measurement (e) and and even greater reduction M2=0.60 for GDP (c).

#### 4. Conclusions

To conclude, we have investigated the off-Hugoniot ablation properties of three candidate ablator materials for ICF capsules. By studying the ablation properties away from the principle Hugoniot we rate how well the current equation of state models for the different materials reproduce the measured performance. Results indicate that the measured off-Hugoniot shock velocities of GDP and HDC fall below that predicted by simulations, while the equation of state of B<sub>4</sub>C better predicts the shock pressure after multiple shocks. We are grateful to the dedication of the NIF operation team. This work was supported by UK MoD and performed under the auspices of Lawrence Livermore National Laboratory under contract DE-AC52-07NA273444. (LLNL-PROC-680805)

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